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Analyzing the effect of carbon prices on wood production and harvest scheduling in a managed forest in Turkey☆

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ABSTRACT

Among terrestrial ecosystems, forests have the largest carbon deposits, and thus play an important role in global climate change. Forests of all ages and types have a significant capacity in sequestration or depositing carbon. Increasing their capacities from this aspect can only be possible through sustainably managed forests. Therefore, in order to increase the carbon stock in forests, carbon management concepts must be integrated into the forestry program. The purpose of this study is to understand how carbon sequestration can affect levels of wood production and harvest scheduling in a forest area operated mainly for wood production, by considering alternative ideas on the current conditions in the given area. Monetary revenue which will be achieved by a 100-year planning horizon with a mixed integer optimization model, the produced wood and the levels of carbon that was sequestrated from atmosphere were investigated under 5 different strategies. Strategies were formed according to the potential unit prices of carbon. In the basic strategy (STR1) carbon price is taken as zero (only wood production revenue), while other strategies, i.e., STR2, STR3, STR4, and STR5 is priced as €8, €35, €55, and €100 per ton, respectively. Regeneration periods of stands and amount of maintenance cuts, which will be extracted from the forest, differ according to the strategies. Results show that when sequestrated carbon unit price is low (STR2 and STR3) or even when carbon has no value (STR1) the management activities in these strategies are almost the same. However, if there is an increase in the value of carbon (STR4 and STR5), with the assessment of different options, it is understood that a much higher level of revenue can be accessible.

1. Introduction

Among all possible options, forests have a special role in potentially reducing or mitigating the release of greenhouse gases to the atmosphere because they are huge stores of carbon, holding more than double the amount in the atmosphere (FAO, 2006). They have different characteristics in terms of their carbon sequestration potential. The amount of carbon dioxide sequestrated in trees or stands depends on many biotic and abiotic factors that affect the photosynthetic conditions. Characteristics such as tree species, site quality, temperature, water and nutrient conditions, health status, and age affect the carbon sequestration potential of forests. Young forests can have high carbon sequestration rates but they have lower amounts of deposited carbon. In contrast, old stands can have the ability to sequester carbon at lower levels due to older tree ages, higher mortality rates, and greater respiration, however, can also have a high amount of deposited carbon (Malmsheimer et al., 2008; Sedjo, 2001).

Forests of all ages and types may have significant capacity to sequester or store carbon. An increase in capacity can be realized through active forest management and careful removal of trees to keep forest species and stocking under control. Thus, while they can provide a wide range of provisioning ecosystem services (wood products and energy) for a local community, forests sequester carbon through normal growth processes. Different mitigation options have unique time sequences, carbon benefits, and costs. Among these options, sustainable forest management for increasing forest carbon stocks while still producing annual yields of timber or other outputs from the forest may make a significant contribution towards reducing global climate change (American Hardwood Export Council, 2012; Asan, 2012; Fenning, 2014; Gharis et al., 2014; IPCC, 2007; Lippke et al., 2011). Raymer et al. (2011) stated that carbon sequestration benefits could be optimized through the regulation of harvesting and regeneration unlike other studies in the literature (Chen et al., 2000; Liski et al., 2001; Nunery and Keeton, 2010; Schlamadinger and Marland, 1996), which

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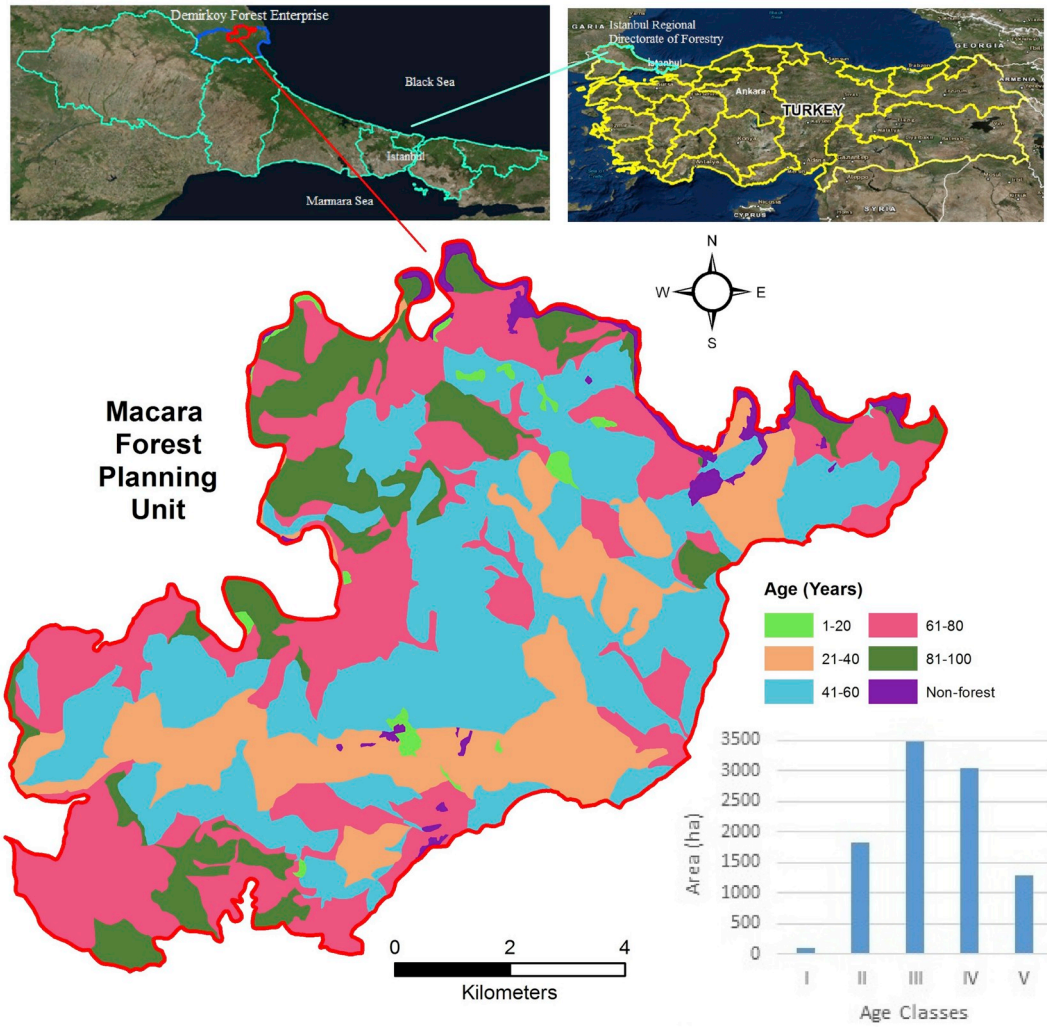

Fig. 1. Geographic position of the study area and age classes of forest stands.

has asserted that the effects of the forest management on carbon sequestration are static. Carle et al. (2016) showed that in their case managing the forest for carbon maximization instead of letting it grow naturally with no harvest or other treatment would increase the carbon stocks by 1.89%. There are several studies considering forest management activities aiming to increase carbon impact. They generally focus on the choice of tree species, application of even or un-even aged management systems, rotation age selection within an even-aged management system, the integration of carbon sequestration to forest planning and the assessment of effects of forest management on ecosystem services or carbon dioxide emission savings from the product storage and substitution of more fossil fuel intensive products by both biofuels and wood construction products (Bettinger et al., 2013; Dong et al., 2015; Duncker et al., 2012; Gharis et al., 2014; Keles and Baskent, 2007; Makineci et al., 2015; Raymer et al., 2011; Sample et al., 2015).

In Turkey, forests occupy 21.7 million ha of land divided into > 1500 forest planning units. These planning units are managed according to the forest management plans developed by the General Directorate of Forestry of Turkey. Within about 8 million ha of forest area (37%), the primary objective is wood production (Food and Agriculture Organization of the United Nations, 2010), in which thoughts about carbon accumulation are not generally considered. The lack of a carbon market or clear carbon prices prevents carbon sequestration from coming to the fore as a management objective among other forest outputs. However, until now carbon sequestration is not the main management objective for most of the planning units; and therefore, it is a necessary ecosystem service that needs to be included in planning projects. The Paris Agreement, which established a framework for climate action and acts as a basis for future cooperation among countries on carbon pricing, encourages countries to cooperate in achieving emission reductions beyond their minimum individual targets already pledged (EDF and IETA, 2016). Based on the greenhouse gas inventory of Turkey in 2012, the total emissions were 440 million tons of carbon dioxide equivalent (tCO_2e). According to the Paris Agreement, Turkey's Intended Nationally Determined Contribution (INDC) is up to 21% reduction in greenhouse gas emissions from the business as the usual level by 2030, and forestry activities can make an important contribution to achieving this level (UNFCC, 2017).

Introducing carbon sequestration objectives can affect forest management in many ways by imposing changes to usual forestry applications. Turkey's forestry plans and policies to implement its INDC are based on increasing sink areas and preventing land degradation through a forest rehabilitation and national afforestation campaign while ignoring sustainable forest management options. Although today there is not an explicit monetary value for carbon in Turkey, long-term carbon trading or carbon taxes has been implemented in many countries, and Turkey has mentioned the use of international carbon pricing initiatives. There are international, regional, national or subnational, or internal carbon pricing initiatives and carbon prices span a wide range of these scales (Qin et al., 2017). In general, 75% of the emissions are priced at less than €3/tC, while the observed prices vary between less than € 1/tC and € 35/tC. This prevalent level of less than € 3/tC seems

to be well below the level of € 20/tC to € 35/tC estimated needed by 2030 to limit the increase in global temperature below 2 °C (World Bank, 2016). In that manner, alternative forest management scenarios that present the highest amount of sequestered carbon or carbon revenue without decreasing the wood production potential of forests have to be considered. Optimal management of forest ecosystems can then be examined through integrated modeling procedures, and ecological responsibilities can also be considered as well.

In this study, we analyzed the current management-planning situation of a forest-planning unit managed for wood production with respect to sequestered carbon and fluctuations in carbon prices. A mixed integer goal-programming model was formed that consider carbon and wood products as joint products. The goal is to optimize the total incomes by scheduling the harvest periods of forest stands for a 100-year planning horizon based on the variable carbon unit prices. Five strategies were created; one to maximize the revenue derived from wood products, and others to maximize the incomes derived from both wood products and carbon sequestration. While keeping all the constraints in the model as constant, only the carbon prices were changed to assess the strategies. Based on the prices in existing carbon pricing initiatives, the carbon price per ton was assumed to be as €8, €35, €55, and €100 per tC in different strategies.

2. Materials

This study was undertaken in Istanbul Regional Directorate of Forestry, Macara Forest Planning Unit, which is operating under Demirköy Forest Enterprise. The study area takes place in Thrace region of Turkey which is located in Europen land between 41°53′33″ and 42°00′24″ north latitude and 27°45′57″ and 27°57′51″ east longitude (Fig. 1). The elevation of the land varies between 15 and 434 m above the sea level. Although in the study area there are few areas with steep slopes, the average slope of forest stands ranges between 5 and 50%.

The total size of the study area is 10,021.5 ha, about 98% of which (9766.5 ha) is covered by forests. Agricultural fields are 206.1 ha, residential areas and forest openings cover 22.8 and 26.1 ha, respectively. The main tree species in the study area is oak (*Quercus* sp.). Almost all of the forest consists of pure oak or stands mixed with beech (*Fagus* sp.). The Macara Forest Planning Unit has operated according to forest management plans since 1958, and its property belongs to the state. According to the current management plan in the area, there are 521 stands (excluding residential and agricultural areas) and 22 different stand types. The size of stands ranges between 0.3 and 73 ha. The total standing wood volume in the forest is 2,826,594 m^3, and the annual increment is 85,867 m^3 per year (GDF, 2003). However, even-aged management systems are applied with the aim of regulating the distribution of forest area to age classes, yet the current age distribution of forest stands is far from optimal as having even areas in all age classes. The total area of the third age class (stand age 41–60 years) is larger than the others (3487.3 ha) while there is only 102 ha in the first age class (Fig. 1).

In the study, the volume growth of oak stands was estimated based on an oak yield table (Eraslan and Evcimen, 1967). In determining the amount of wood products in different stand ages, the rates proposed by Sun et al. (1978) were used. Moreover, for the purpose of production and analysis of various digital maps, a Geographic Information System software program (ArcMap 10.4) was used. In generating the optimal harvest scheduling for a 100-year planning horizon according to various scenarios, the GAMS 24.5.6 (General Algebraic Modeling System) optimization program was used.

In the Macara Forest Planning Unit, primary wood products desired from the forest are saw logs, mine poles, industrial wood, and firewood. The average sales price for 1 m^3 of these products in recent years has been €53, €45, €23, and €15, respectively. There are no limits in terms of amount of production of these product types, but due to social needs the production of at least 2000 m^3 of firewood (40,000 m^3 in a 20-year period) every year is expected. Taking labor and operational capacity into consideration, it is foreseen that in each time period (20 years), regeneration practices should be implemented in an area of 100–200 ha, and the volume to be removed from the forest during final harvests is expected not to exceed 50,000 m^3 per year.

In order to ensure continuity in product flow, it is intended not to have > 10% fluctuation in periodic wood production quantity. At the end of the planning horizon (100 years) standing wood volume and the amount of carbon are required not to fall below their current levels. The forest is managed under even-aged systems, and natural regeneration based on shelter wood trees is applied. The regeneration period is taken as 20 years and the rotation age is assumed to be 100 years. Under these conditions, the aim of the study is to determine which stands in the Macara Forest Planning Unit could be applied a final harvest (and regenerated) and how much wood production could be obtained by applying maintenance cutting activities to other stands in order to maximize economic values.

3. Methods

3.1. Development of models for carbon sequestration

For the calculation of the amount of sequestered carbon in stands, the approach recommended by IPCC (2003) in Land Use, Land Use Change and Forestry–Good Practice Guidance (LULUCF-GPG) was used. Standing volume difference in two consecutive periods was taken, and the amount of carbon in the obtained periodic volume increment was calculated. When calculating the volume increment, the amount removed from the forest volume by the maintenance or regeneration was excluded from the gross increment. Thus, the resulting net volume increment was multiplied by coefficients proposed by Asan et al. (2002) and Tolunay (2011), and the amount of carbon accumulated in aboveground biomass was determined. The analyses are based only on the amount of carbon in aboveground living biomass. The formula used for this purpose is given at Eq. (1).

$$m^c = I_V E_f W_o C_r \quad (1)$$

m^c: Over-ground carbon amount (tons)
I_V: Volume increment in a period (m^3)
E_f: Biomass expansion factor (1.310 for deciduous trees)
W_o: Oven dry weight (0.541 for deciduous trees)
C_r: Ratio of carbon in the biomass (0.480 for deciduous trees)

Carbon values of stands were calculated by multiplying the amount of carbon sequestered from the atmosphere from each stand during a time period by the projected unit price of carbon. Since a carbon market has not been formed so far, a specific figure for carbon unit price is not available yet. Based on the prices in existing international or national carbon pricing initiatives, the carbon price per ton was assumed to be as follows; €8, €35, €55, and €100 per tC.

3.2. Determining the wood production values of stands

In the analyses, stumpage values of stands were used to assess the wood production values. The sale prices are determined by calculating the cost of per unit volume where it is planted, that is, in the forest where the wood is grown and by adding various costs and entrepreneurs' profit. Therefore, in the market, by working backward, removing costs from the sale price of a product formed according to the free market conditions, the value of wood in the forest where it is standing can be calculated (Eq. (2)). Entrepreneurs' profit is suggested to be ranging between 8 and 30% of the sum of stumpage value and costs (Firat, 1971). In this study, it is taken as an average of 20% for the convenience for the study.

During the processes of cutting and transportation of woods, charges such as cutting, skidding, and handling were associated with the range of products (saw logs, poles, industrial wood, and firewood) and they were calculated separately for each stand. Other costs apart from these were not taken into account.

$$t = \left(\frac{S_p}{1+m}\right) - c \quad (2)$$

t = Stumpage value (€)

S_p = Selling price (€)

c = Costs (total amount of logging, carrying, and transportation costs)

m = Entrepreneurs' profit (0.20)

By means of taking the average of auction sale of the last 5 years regarding wood product types for oak into account and the excluding entrepreneurial profit; values of stands in the forest depot (saw log: €53/m^3, pole wood: €45/m^3, industrial wood: €23/m^3, firewood: €15/m^3) were calculated. It should be noted here that, it is assumed that these prices will not change during the planning horizon. By associating the unit costs for the production of wood types and ratios of wood types within the volume of total tree volume in any given stand, total costs were calculated for each stand. In determining the obtained saw log, pole wood, industrial wood, and firewood from a stand, the rates calculated by Sun et al. (1978) were used. Then, these results were multiplied with stand volume in order to find the quantity of product range in all stands.

In order to calculate skidding costs, skidding distance and average slope must be determined. As for skidding distance, the shortest distance to the nearest road of stands center of gravity was considered. The average slope was calculated by using digital elevation models and related tools of the GIS software.

3.3. Composing planning model and strategies

Five strategies were established one of which aims to maximize the Net Present Value (NPV) of incomes derived only from wood production and others both from wood and carbon production. When creating strategies, all the constraints in the model were kept constant but only carbon prices were changed. The constraints such as; fluctuation in the production of wood not to be > 10% between two consecutive periods, stands not to be regenerated before the age of 100, and the total area of the stands that will be regenerated should be < 200 ha took place at the same level in all strategies. The optimal size for the total area of stands that will be regenerated in a period (A) is dependent on the whole planning unit area (F), rotation age (U), and length of periods (n), moreover in this case it is near to a level of 2000 ha (A = F*n / U). Considering the current situation of the forest enterprise in terms of labor, operational capacity, and recent practices the level of 200 ha was assumed to be enough in a period of regeneration. However, although a periodic total amount of wood produced from the stands was not restricted, and up to 50,000 m^3 is intended to be obtained by regeneration of stands. Also, constraints, namely, the standing volume of wood not to be less than the current level at the end of planning horizon and the amount of firewood to be produced in each period for social reasons not to be < 40,000 m^3, were included in the model. When calculating the NPV of periodic income, the discount rate was taken as 5%. Information on various strategies and constraints is shown in Table 1. Only the carbon prices were changed based on the strategies, while all of the remaining constraints and their levels are the same for the five strategies.

The created model attempts to maximize objective function by adjusting regeneration periods of 521 stands in the planning unit, maintenance cutting, and amount of volumes to be extracted. For this purpose, 100-year planning horizon is divided into five 20-year periods. There are totally 6 alternatives for any stand based on regeneration time. First one is not to be regenerated at all while the others consist being subject to final (regeneration) cuts in any of the 20-year periods. In determining the volume of any period or calculating the amount of volumes to be transferred to next period, increment percentage simulation method (Eraslan, 1981) was used (Eq. (8)). Volume changes will be realized according to Eq. (8) until the stands are regenerated, and after they are regenerated they have been assumed to have optimal growth conditions according to values in the yield table (Eraslan and Evcimen, 1967). The amount of the volume to be extracted from stands by maintenance cuttings ($X_{k,i,j}{}^{m}$) has been limited by upper and lower bounds (Eq. (11)) depending on the development stage of the stands and it is intended for the model to decide on the most appropriate rate that will maximize the objective function for the related stand. Lower and upper limits of maintenance cutting depending on the development stage of stands are as follows: young stage (20–30%), pole stage (10–20%), thin wood stage (5–10%), medium and thick wood stage (1–5%). The whole model developed, the explanation of parameters and decision variables are given below. When running the model for STR1 (only maximization of wood income) the parameters related with carbon were removed.

$$\max z = \sum_{j=1}^{N}\left(\left(\sum_{k}\sum_{u=1}^{n^{pr}}(p_u^w - c_{k,u})m_{k,u,j}^w\right) + p^c m_j^c\right)(1+\alpha)^{-n(j-1)}$$

(*theobjective function maximizing the NPV from wood and carbon incomes*) (3)

where

$$m_j^c = \sum_k \sum_{i\neq j+1}(V_{k,i,j+1} - V_{k,i,j})E_f W_o C_r \quad (\textit{amount of carbon that is taken from atmosphere}) \quad (4)$$

$$m_{k,u,j}^w = \sum_i q_{k,i,u,j}^m X_{k,i,j}^m + q_{k,i,u}^r X_{k,i,j}^r \ (\textit{amount of wood products}) \quad (5)$$

$$X_j^p = \sum_{k,i}(X_{k,i,j}^r + X_{k,i,j}^m) \ (\textit{periodic wood volume to be extracted}) \quad (6)$$

$$V_{k,i,1} = V_k^0 A_k y_{k,i} \ (\textit{actual wood volume of a stand}) \quad (7)$$

$$V_{k,i,j+1} = V_{k,i,j}(1 + nr_{k,i,j}^{growth}) - X_{k,i,j}^m, \forall\, k, i, j : i \neq j \ (\textit{growth balance between sequential periods}) \quad (8)$$

$$V_{k,j,j+1} = V_k^{10} A_k y_{k,j}, \forall\, k, j \quad (\textit{initial volume of a stand after regeneration}) \quad (9)$$

Table 1
Objectives and constraint levels in the planning model.

Strategy ID	Objective	Carbon price (€/ton)	Constraints	Constraint level
STR1	Max NPV of wood	–	Wood flow fluctuation	< 10%
STR2	Max NPV of wood and carbon	8	Regeneration area	< 200 ha
STR3	Max NPV of wood and carbon	35	Amount of final harvest	< 50,000 m^3
STR4	Max NPV of wood and carbon	55	Harvesting age	> 100 years
STR5	Max NPV of wood and carbon	100	Fire wood production	> 40,000 m^3

$$X^{r}_{k,j,j} = V_{k,j,j}(1 + nr^{growth}_{k,j,j} /2), \forall\ k, j \quad (\textit{wood volume extracted by regeneration cuttings}) \tag{10}$$

$$\underline{r}^{m} V_{k,i,j} \le X^{m}_{k,i,j} \le \overline{r}^{m} V_{k,i,j}, \forall\ k, i, j : i \neq j \quad (\textit{limits of wood volume extracted by maintenance cuttings}) \tag{11}$$

$$(1 - r^{p})X^{p}_{j} \le X^{p}_{j+1} \le (1 + r^{p})X^{p}_{j}, \forall\ j \quad (\textit{constraint for periodical wood flow balance}) \tag{12}$$

$$\sum_{i} y_{k,i} = 1, \forall\ k, \quad (\textit{constraint for choosing only one scenario among 6}) \tag{13}$$

$$\underline{A}^{p} \le \sum_{k} A_k y_{k,i} \le \overline{A}^{p}, \forall\ i, \quad (\textit{constraint for periodical regeneration area}) \tag{14}$$

$$\sum_{k,i} V_{k,i,N+1} \ge \sum_{k,i} V_{k,i,1}, \quad (\textit{constraint for ending inventory}) \tag{15}$$

$$\sum_{k,i} X^{r}_{k,i,j} \le \overline{R}, \forall\ j, \quad (\textit{constraint for total amount of regeneration cuttings}) \tag{16}$$

The parameters:

N: the number of the periods (5),

n: the length of the periods (20),

p_u^{w}: the unit price of the wood product u,

$c_{k,u}$: the cost of carrying the required materials from stand k, for product u,

p^{c}: the unit price of carbon,

r^{c}: the ratio of the amount of carbon, in a unit volume of wood,

α: the interest rate (5%),

A_k: the area of the stand k,

$D_{k,i,j}^{m}$: the average diameter of the trees in stand k in period j, given that stand k is regenerated in a different period i,

$D_{k,i}^{r}$: the average diameter of the trees in stand k at the period i,

V_k^{0}: the actual volume of wood in stand k, in a unit area of land,

V_k^{10}: the wood volume of a new regenerated stand k,

$r_{k,i,j}^{growth}$: the growth rate of the volume of wood in stand k in period j, given that stand k is subject to regeneration in a different period i,

$\overline{r}^{m}$, $\underline{r}^{m}$: allowed upper and lower bounds on the ratio of the volume of the wood that is obtained by maintenance cuttings,

r^{p}: allowed change in the ratio of volumes of woods cut at consecutive periods,

$\overline{A}^{p}$, $\underline{A}^{p}$: allowed upper and lower bounds on the total area that can be made regeneration cuts,

$\overline{R}$: allowed upper bound on the amount of wood that can be obtained by regeneration cuts,

$q_{k,i,u,j}^{m}$: the ratio of obtained wood product u, of the maintenance cuts in period j, in stand k, if it has been regenated at period i,

$q_{k,i,u}^{r}$: the ratio of obtained wood product u, of the regeneration cuts in period i, in stand k.

The decision variables

$y_{i,k}$: 1 if the stand k is subject to regeneration cut at period i,

$X_{k,i,j}^{m}$: the wood volume obtained by maintenance cut at period j from stand k, given that the stand k has a regeneration cut at period i,

$X_{k,i,j}^{r}$: the wood volume obtained by regeneration cut at period j from stand k, given that the stand k has a regeneration cut at period i,

X_j^{p}: the total wood volume that is obtained in period j.

$V_{k,i,j}$: the wood stock of stand k in period j, given that the stand k has a regeneration cut at period i,

m_j^{c}: the amount of carbon that is absorbed from the atmosphere in period j,

$m_{k,u,j}^{w}$: the amount of wood product u from stand k in period j.

4. Results and discussion

In the planning model, two objective functions were created to maximize the total income derived from (1)-only wood production, and (2)-both wood production and carbon accumulation at the end of the planning horizon. The model was then run separately for these two objective functions without changing constraints and their levels. In this way, the optimal values to be obtained under the same constraints according to different objective functions were determined. In doing so, how the changes in the price of carbon have an effect on the level of wood production and regeneration periods of stands when the prices of wood product range are kept constant was observed.

When analyzing the NPV obtained from timber harvests per period it is shown that at the end of the 100 years the highest income is in STR1 (€13,907,982), while the lowest income obtained is in STR5 (€7,688,508) (see Fig. 2). Although STR1, STR2, and STR3 values are too close to each other, it is observed that generally between the strategies, as the carbon price increases the incomes derived from the production of wood also decreases. Periodically, wood production income decreases continuously in all strategies. The reason for this situation is that in order to maximize the NPV, the model has a tendency to adopt the options that will generate more income in the initial periods.

Periodic change of the income derived from wood production and carbon accumulation is given in Fig. 3. At the end of the planning horizon, the highest income occurs in STR5, which has the highest carbon unit price (€59,600,711). In STR1, there is only income from wood production, which results in the lowest income. It is interesting that the incomes decline continuously from first towards the last period and the difference between the values decrease as well. While the ratio of incomes obtained in STR5 and STR1 is nearly 5 in the first period, this ratio drops to about 2 in the last period.

When total wood production (m^3) obtained by final harvest (regeneration) and maintenance cutting was examined, it is seen that after 100 years the highest production took place in STR1 (2,260,393 m^3). It was followed by STR2 (2,252,316 m^3), STR3 (2,223,366 m^3), STR4 (1,771,852 m^3), and STR5 (1,281,424 m^3), consecutively. Periodic variations in the total wood production are illustrated in Fig. 4. While periodic values in STR1, STR2, and STR3 varied with each other very closely, with increasing carbon price, in all strategies, production quantities of wood were decreased. The amount of wood production decreased in the first three strategies in the second period, STR5 in the third period, STR4 in the fourth period. As there was a wood production flow restriction of 10% between periods, large deviations in harvest volumes were not observed. Periodic changes in the amount of wood production achieved by maintenance cutting activities were similar to the values of the total wood production.

Although there is no restriction on the upper limit on the amount of

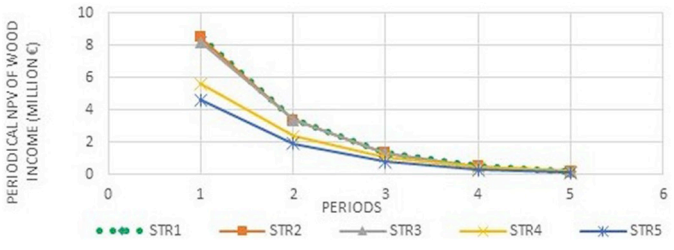

Fig. 2. Periodic change of the NPV of wood production.

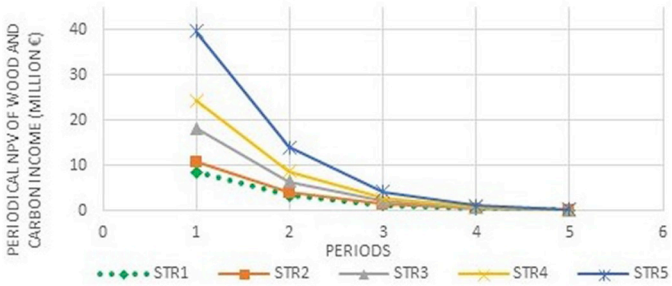

Fig. 3. Periodic change of the NPV of both wood production and carbon accumulation.

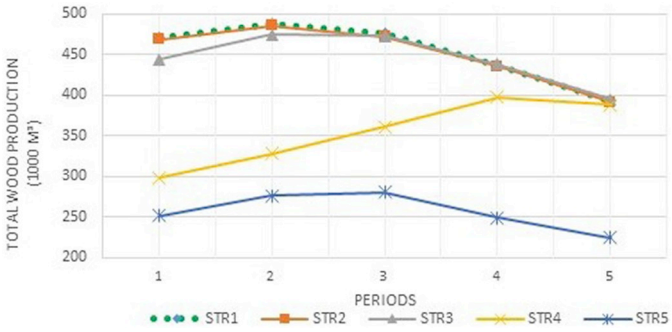

Fig. 4. Periodic variation of the total wood production.

total wood production (from regeneration and maintenance cuttings), periodic wood production in all strategies never exceeded 500,000 m^3 (Table 2) in these analyses. When the objective function is to maximize incomes from timber, timber harvests from final cuttings per period were close to the 50,000 m^3 used as a constraint, in the rest of strategies the values were much lower. Assmuth (2015) showed that when carbon storage has an economic value, thinning is somewhat postponed by implying higher stand volume and larger trees without carbon pricing are targeted. In our analysis, generally, as the price of carbon increased, the amounts of products to be obtained by final harvest or regeneration cuttings were realized at lower levels. This is also true for maintenance cuttings. So, the total amount of cuttings (regeneration and maintenance cuttings) decreases with the increasing price of carbon.

At the end of 100 years, a total amount of carbon sequestered from the atmosphere was estimated to be a maximum of 1,280,560 tons in STR5. This is followed by STR4 with 1,083,630 tons. Compared to these values, we can see that in the other strategies, the amount of carbon sequestered was projected to be lower, and they are similar to each other. When applying the other strategies, the amount of carbon

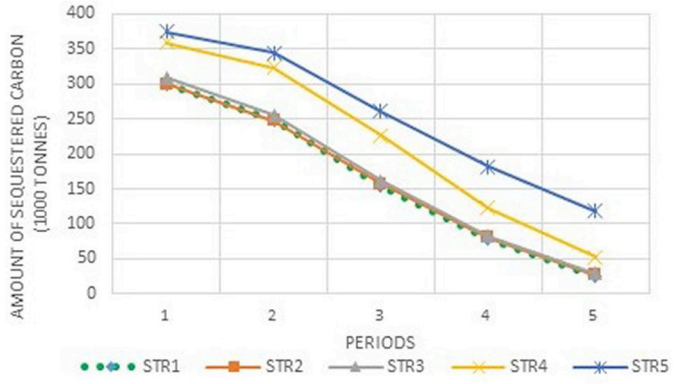

Fig. 5. Periodic variation of the amount of carbon sequestrated based on the strategies.

sequestered was lower ranging from 806,788 in STR1 to 836,689 in STR3. In all strategies, the amount of carbon sequestrated from the atmosphere was at the maximum level in the first period, but reduced continuously over the following periods (Fig. 5).

In terms of temporal values of the same quantities, the NPV of the products that will be produced at a time close to today will likely be higher because of the discount rate. Therefore, the model is trying to realize maximum production at the periods as close to present day to achieve the highest values as much as possible based on the objective function by considering the interactions with and among the other constraints. Since there is not a constraint in the model governing the NPV fluctuations between periods, income and amounts of carbon sequestrated from the atmosphere continually decrease from the beginning period towards the end of the planning horizon in all strategies. Although, losses from ecosystem by wood extraction do not continually increase (Fig. 4), the realization of this situation occurs because of reduction of carbon sequestration potential and volume increment of stands due to their excessive aging after some periods. So, the model attempts to evaluate the stands in the previous periods when the amount of growth and carbon sequestration together with their nominal values are higher. If there is an intention to prevent this condition, constraints, which will periodically increase volume increment or amount of sequestrated carbon, should be added to the model. Another option is to increase the amount of forest area that can be regenerated in a period, and thus, allow greater amounts of old stands to be regenerated. Otherwise, at the end of the planning horizon, in terms of the distribution of age classes of stands, there will be a situation, in which there is an accumulation in old stands.

The periods in which the stands will be regenerated and amounts of maintenance cutting to be extracted vary according to different

Table 2
Wood production levels obtained by regeneration and maintenance cuttings based on strategies (m^3).

Wood source	Period no.	STR1	STR2	STR3	STR4	STR5
Regeneration	1	49,944	48,359	49,794	47,203	33,563
	2	49,916	48,637	49,869	38,761	43,956
	3	49,944	46,801	49,713	49,343	43,956
	4	49,997	45,199	49,968	49,460	41,123
	5	50,000	48,929	49,999	50,000	50,000
Maintenance cutting	1	420,574	420,340	394,251	251,031	217,571
	2	436,729	436,608	424,548	289,296	232,291
	3	424,905	425,037	422,993	311,520	236,612
	4	385,992	389,819	388,032	347,489	208,074
	5	342,390	342,587	344,200	337,749	174,278
Total	1	470,518	468,699	444,044	298,234	251,134
	2	486,645	485,245	474,417	328,057	276,247
	3	474,850	471,838	472,706	360,863	280,568
	4	435,989	435,018	437,999	396,949	249,197
	5	392,390	391,516	394,199	387,749	224,278
Total in 100 years		2,260,393	2,252,316	2,223,366	1,771,852	1,281,424

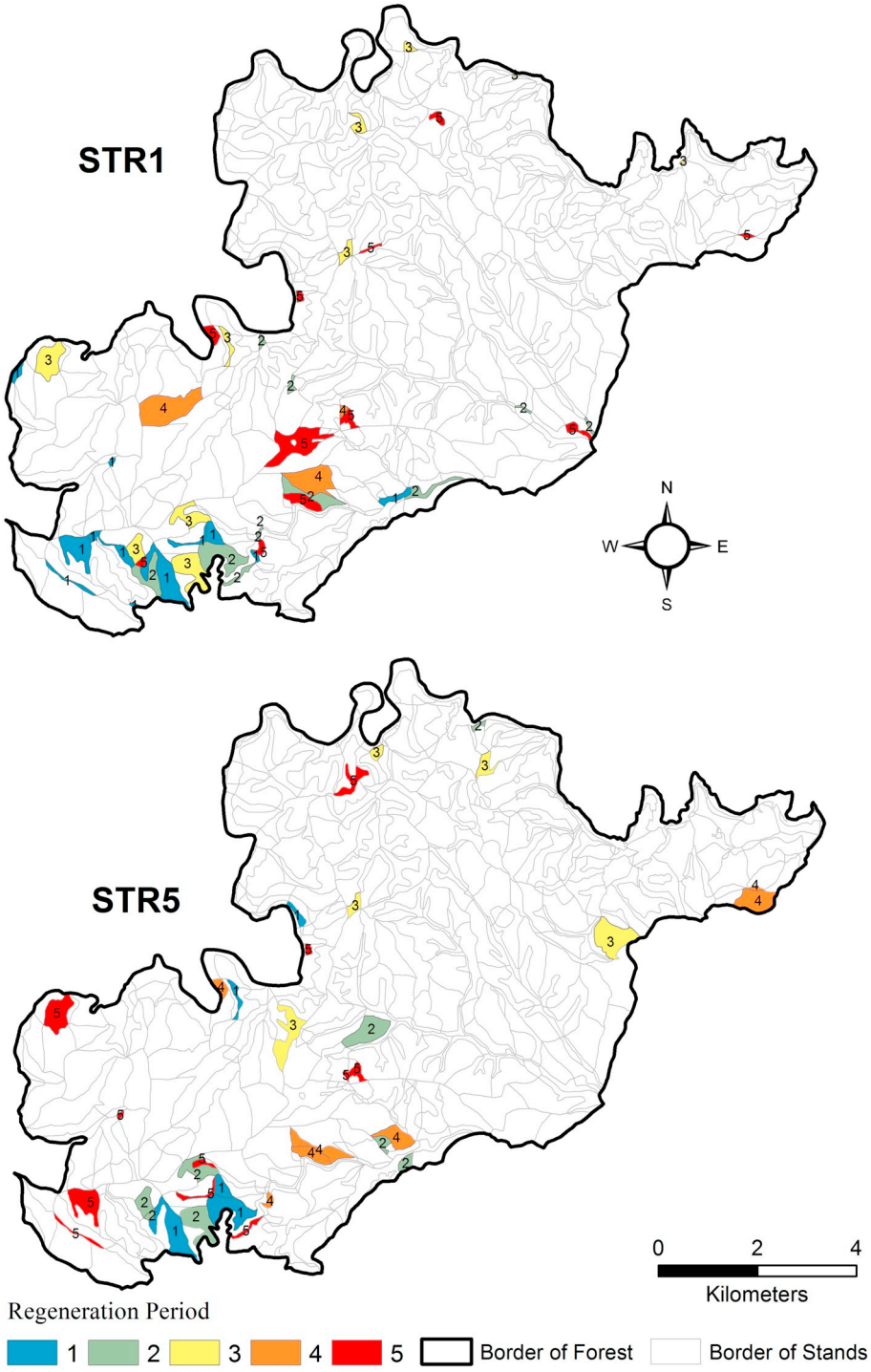

Fig. 6. Regeneration period of forest stands based on STR1 and STR5.

strategies. Hence, the spatial distribution of forest stands will be different according to different strategies and implementers have to know when, where, and how much the forestry treatments will be realized based on the objectives. If STR1 and STR5 are selected, which are the most diverse scenarios from each other with €8 and €100 per tC, the periods in which the stands in the forest will be regenerated is given in Fig. 6. In both strategies, the model seeks to identify the options that will bring the highest income considering constraints in the 100-year planning horizon. Therefore, in different periods it tries to regenerate the stands that are less inclined and closest to the market in order to reduce the costs. In other words, the regeneration of any stands changes based on the selected strategy. The stands that are chosen by the model to be regenerated are mostly aggregated at the southern part of the forest where the forest store is closer to reduce the transportation costs.

Qin et al. (2017) analyzed the effect of current carbon prices (roundly €3, €7.5, and €10 per tC) in China on the optimal forest management plans. They found that current prices had no effect on optimal plans and suggested a minimum price of €105 per tC to provide the financial incentive for the forests to function as a significant carbon sink. In our analysis, wood production ratios are generally similar for the first three strategies and so the prices of €8 or €35 per tC does not have significant effects on wood production levels. As a result, it can be said that a price of more than €35 per tC (~€120/tCO_2e) which is near to the level needed to limit the increase in global temperature can be

appropriate on trade-offs between carbon and timber management for the study area.

5. Conclusion

There may be different options among forestry activities for carbon sequestration that come with lower costs (making them cost effective). The most suitable among these options can be determined by modeling forest systems because it is possible to forecast the future structure of the forests under different management regimes. In this study, moving from the actual facts and circumstances in a forest for wood production, forest structure is modeled and the situations that emerged as a result of the different strategies were evaluated. It is revealed that the forest structure that will be planned for the situations when the unit price of sequestrated carbon is low (STR2 and STR3) almost coincides with the management activities in which the aim is wood production (STR1). However, if there is an increase in the value of carbon (STR4 and STR5), a much higher level of income can be realized. Together with this, some constraints to regulate the periodic fluctuation of income are needed; otherwise, it continuously decreased along the planning horizon. To reflect the actual situation for the study area, the periodic regeneration area is limited to be smaller than 200 ha. Unfortunately, this level is not enough to regenerate the whole forest within the planning horizon and will result in the forest becoming very old, and excessive ages will lead to decreases in both carbon sequestration and wood production potential. In the future, it would be beneficial to analyze the effect of different regeneration area sizes or rotation ages, or apply the optimal periodical area of regeneration in the forest so that society can benefit from the wood production or carbon sequestration function of it in a more productive way.

All forests sequester carbon at different levels depending on their current structure and health. Therefore, more emphasis should be given to forestry options associated with carbon trading and reducing carbon emissions. With this perspective, carbon sequestration through forest growth is gaining importance as a forest function, and should be considered in all aspects of a forest area. For example, the forests in the areas that have very steep slopes or are in remote locations from potential markets, and thus are not suited for industrial forestry, might be used for carbon sequestration purposes. However, in cases of modern forest management, with many alternatives and constraints, the most affordable way cannot be discovered with classic approaches, thus, forestry should focus on modeling studies. The spatial distribution of forest stands has a significant impact on the level of expected output from these ecosystems. In order to ensure sustainable ecosystem services and increase their contribution to society, the spatial structure and temporal variations of forests must also be controlled by planning activities.

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